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Section 7. Plasma edge diagnostics and physics

Ion temperature measurement using an ion sensitive probe in the LHD divertor plasma

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Abstract

The first reliable measurement of ion temperature in the divertor plasma of the Large Helical Device has been done by using an ion sensitive probe. The satisfactory current–voltage characteristics of the ion collector for evaluating the ion temperature were obtained at the outer part of the divertor leg. Furthermore, simultaneous ion and electron temperature measurements were successfully done in this part. The results show that the ion temperature is higher than the electron temperature in the part. There is a possibility that the profiles of the evaluated ion temperature which shows relatively higher than the electron temperature at the outside of divertor leg are qualitatively explained by particle's orbits around the edge and divertor region.

Keywords: Plasma diagnostics; Ion temperature; Ion sensitive probe; Probe characteristics; Divertor plasma; LHD

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1. Introduction

It is important to know the characteristics of the edge and divertor plasmas, in order to improve confinement and operate high performance plasma in magnetic fusion experimental devices. Ion temperature (T_i) is one of the key parameters for characterizing these plasmas. Concerning the measurement of T_i, a Doppler broadening measurement of ion emission lines is used as an optical method. A retarding field analyzer [1], a rotating double probe [2], an asymmetric cylindrical double probe [3] and an ion sensitive probe (ISP) [4,5] are well known as particle measurements for T_i.

The active control of edge plasma using the helical divertor for improved confinement and the steady-state operation of high performance plasmas is one of the basic physical objects of the Large Helical Device (LHD) [6]. Experimental studies have been performed about electron temperature (T_e) and electron density (n_e) measurement in the divertor plasmas in LHD [7,8]. However, T_i in the edge and the divertor plasmas has not been measured up to now. So far, it is found that the plasma parameters in this region, especially T_e, are drastically changed in spite of the relatively wide divertor leg with the width of a few cm. Conventional optical methods for measuring the T_i have a difficulty to obtain the local values and the profile of T_i because the evaluated values are integrated (averages over) along the line of sights. Therefore, in order to measure the profile of T_i in this region, it is necessary to prepare a high spatial resolution diagnostic system. With respect to the purpose, an ISP proposed by Katsumata [4] is expected to be useful because of its simple structure and high spatial resolution.

An ISP functions in the magnetized plasmas, and simultaneous measurements of T_i, T_e, n_e and plasma space potential (V_s) are possible. The concept of T_i measurement using ISP is shown in Fig. 1(a). The difference of the

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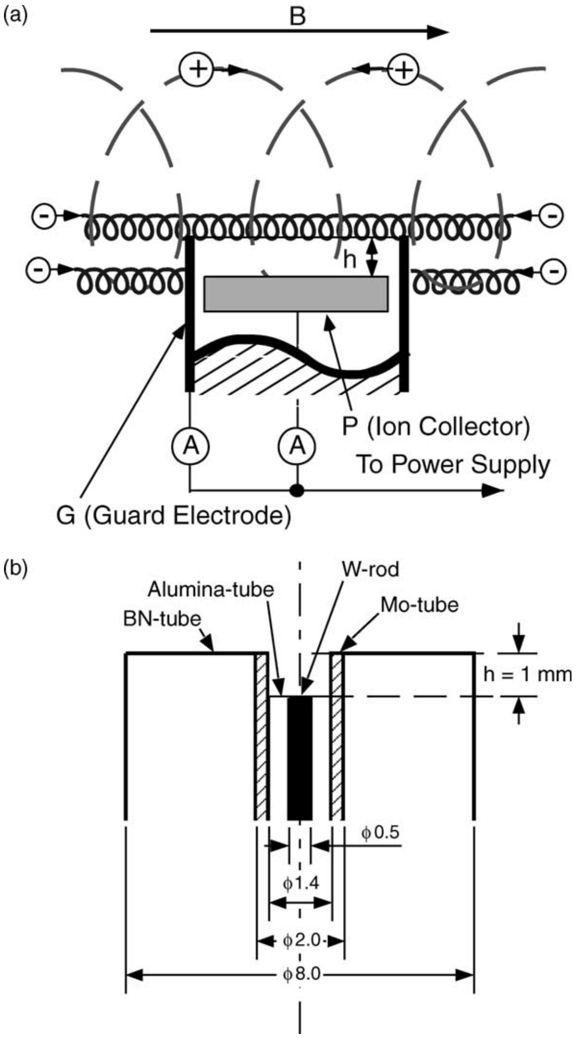

Fig. 1. (a) Conceptual schema of behavior of charged particles around an ISP. Note that the dimensions of this schema are different from that of the real configuration. (b) The structure of ISP head designed for the measurement of the divertor plasma in LHD. The inner electrode is a flat end of a tungsten rod. The outer electrode is molybdenum tube. The value of h was set to 1.0 mm.

Larmor radii between ions and electrons is utilized to separate them. A typical ISP consists of two electrodes, an ion collector (referred to as 'P' or 'inner electrode') and an electron guard electrode (referred to as 'G' or 'outer electrode'). The inner electrode is located at the coaxially inside of the cylindrical outer electrode. These electrodes are electrically isolated. The inner electrode collects only ions even when the biasing voltages applied to both electrodes are positively beyond the V_s. The outer electrode works as a fence to prevent electrons flowing into the ion collector. The estimation of T_i can be performed by analyzing of the current–voltage (I–V) characteristic of the inner electrode. T_e is also evaluated by analyzing the I–V characteristic of the outer electrode.

The purpose of this study is to investigate the ion's behavior in the LHD divertor plasma by using an ISP. In this paper, we describe the first results of the T_i measurement using the ISP in the divertor plasma of LHD. Obtained I–V characteristics for evaluating T_i and T_e and profiles of plasma parameters including T_i in the divertor leg of LHD are discussed.

2. Experimental setup

Figure 1(b) shows a schematic of the ISP head designed for the LHD divertor plasma measurement. As mentioned above, the ISP electrode consists of two electrodes: an ion collector and an electron guard electrode. A flat-top tungsten rod and a molybdenum tube were used for the inner and the outer electrodes, respectively. The outer electrode was covered by a boron-nitride tube. In order to insulate between the inner and the outer electrodes, an alumina (Al_2O_3) tube was used. The distance between the tops of the ion collector and the outer electrode is defined as 'h' as shown in Fig. 1. The h value for the divertor plasma in LHD was evaluated from the following relations developed by Katsumata [4].

$$10\rho_e < h_c < 10\lambda_d + 10\rho_e, \tag{1}$$

where 'h_c' is the critical value of h in order to obtain a satisfactory ion collector signal, ρ_e is the Larmor radius of electron, λ_d is the Debye length. Assuming the typical plasma parameters and field strength in the divertor plasma in LHD as $n_e = 5 \times 10^{18}\ m^{-3}$, $T_e = 20$ eV and the magnetic field $(B) = 1$ T, the h_c is estimated to be 0.3 mm. This estimation assumes that the ISP is inserted in the plasma perpendicular to the magnetic field lines. The experimental configuration in the LHD is shown in Fig. 2. The ISP electrode is installed on the top of the reciprocating type fast scanning Langmuir probe system [9,10]. It is installed from the bottom port of LHD. In the divertor leg, the angle between the magnetic field lines and the direction of the ISP movement is about 30°. Therefore, we take the angle into account to evaluate the h. In this experimental condition, the inner electrode was set on the position of $h = 1.0$ mm.

Figure 3 shows the electric circuit and the data acquisition system for the ISP measurement in LHD. The probe bias voltage (triangular wave, −110 to +110 V, 200 Hz) was applied from the bipolar power supply to the both electrodes of the ISP. The reference potential for the circuit is the ground (vacuum vessel's) potential. In order to measure T_i successfully, it is necessary to keep the potential of both electrodes equal [4,11]. Therefore, we selected the resistances ('R_p' for inner

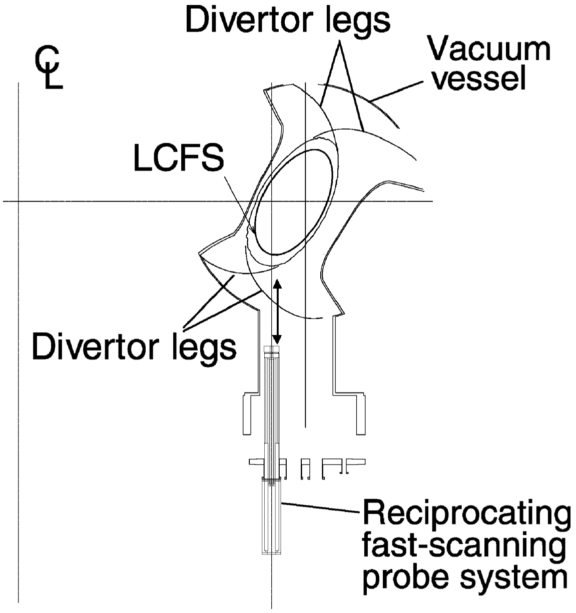

Fig. 2. Configuration of the reciprocating type fast scanning Langmuir probe system installed with the ISP electrode. The reciprocating paths of the ISP cross the divertor leg as shown by arrows. The speed of reciprocating motion is 3 m/s.

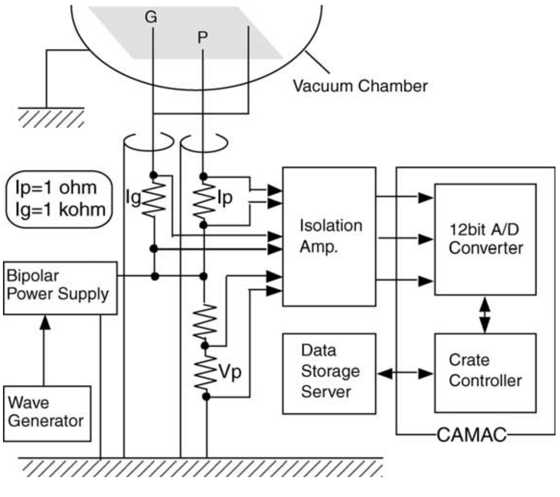

Fig. 3. The electric circuit and the data acquisition system for measurements of T_i and T_e using the ISP in LHD.

electrode, 'R_g' for outer electrode) for detecting probe currents as 1 kΩ and 1 Ω, respectively, in order to decrease the influence of potential drops. These voltage signals across the resistors were fed to the digitizer via isolation amplifiers. The resolution and the sampling rate of the digitizer were 12 bits and 100 kS/s, respectively.

3. Experimental results and discussion

3.1. *I–V characteristics of the ISP*

The measurements of plasma parameters in the divertor leg in LHD using the ISP were performed in hydrogen plasma with the NBI heating in the operational configuration with the magenetic axis position (R_{ax}) of 3.60 m, a toroidal magnetic field strength of 2.887 T. It should be noted that in the discharges mentioned in this paper, the toroidal field direction was reversed from the standard direction. Figure 4 shows typical *I–V* characteristics of the inner and the outer electrodes of the ISP obtained during the discharge of #31256. As mentioned above, the ISP is able to measure T_i, T_e, n_e and V_s at the same time. Their profiles (as for T_i and T_e) in the divertor leg will be shown in Section 3.2. As shown in Fig. 4(a), clearly different characteristics are obtained from both electrodes. The *I–V* curve of outer electrode shows the same characteristic as a conventional single Langmuir probe. On the other hand, the *I–V* characteristic of the inner electrode shows no

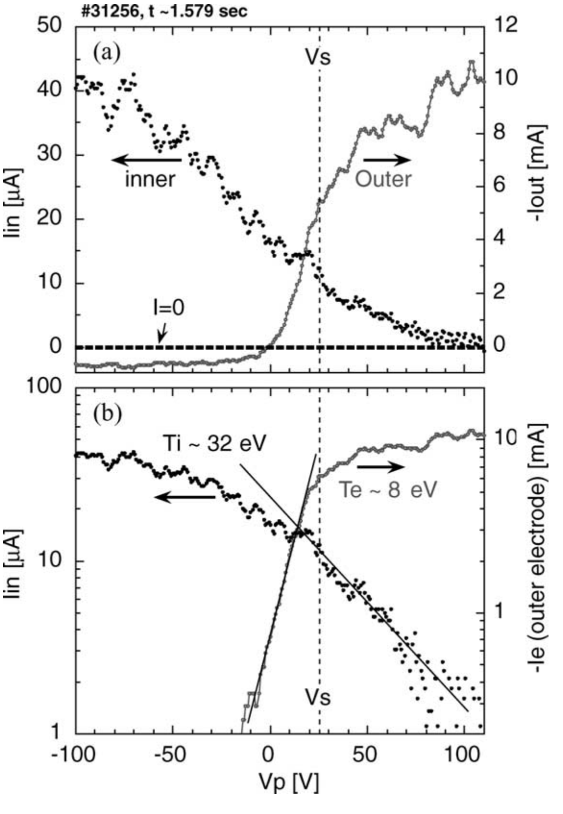

Fig. 4. Comparison between *I–V* characteristics of the inner and the outer electrodes of the ISP; (a) in the linear scale, the current of the inner electrode (I_{in}) is almost zero at even positive biased voltage (V_p) in comparison with V_s (b) results of the estimation of T_i and T_e in the logarithm scale.

negative current at even positive probe voltage. It is reasonable to suppose that electrons are prevented from coming into the inner electrode. T_i is estimated by the exponential fitting of this characteristic as shown in Fig. 4(b). In this case, the estimated T_i is about 32 eV. On the other hand, T_e is estimated to 8 eV.

3.2. Profile of T_i in the divertor leg

Figure 5 shows the profile of T_i, T_e, V_s and connection length of magnetic field lines (L_c) in the divertor leg along the movement path of the ISP. Note that the condition of core plasma during the probe scan was almost constant. In the hatched region in this figure, *I–V* characteristics of the inner electrode are similar to that shown in Fig. 4. Namely, the electron current is suppressed by the outer electrode and little electron current reached the inner electrode. The estimation of T_i is possible with high reliability, and shows the higher value compared with T_e at the same point in this case. Unfortunately, these successful *I–V* characteristics of the inner electrode are obtained only in the hatched region, though the T_e estimation is succeeded in the whole position in the divertor leg. At the center region of the divertor leg, the ion current did not reach to zero. Furthermore, the V_s was close to or exceeded the limit of probe voltage. Therefore, it is impossible to judge the reliability of the separation of ions and electrons on the inner electrode. One of the possible reasons for the problem is the wide range of the plasma space potential in the leg. The potential at the center of the divertor leg is more positive than that at the edge of the leg. The range of the probe voltage was restricted by the power supply, and was not enough for measuring the whole region of the leg. The left side of the peaks of T_e corresponds to the private region (see the configuration of the ISP driving system in Fig. 2). In this region, the measured ion currents on the inner electrode are too noisy to evaluate T_i in spite of the T_e and n_e are similar to those of the hatched region. The profile of T_e has a similar structure to that of L_c. This result is consistent with the result of the particle flux measurement on the divertor plate in LHD [8]. On the other hand, in order to discuss the profile of T_i, the large error must be taken into account except for the results in hatched region, nevertheless, the profile seems to be broadened as compared with the profiles of T_e and L_c. According to the calculation of the particle's orbit in the edge and the divertor region in LHD, the existence of the loss channel of fast ions at the open field side corresponding to the hatched region in Fig. 5, not the private region side, is pointed out [12]. This result suggests the existence of ions whose temperature is relatively high at the outer region of the divertor leg, and is qualitatively consistent with the T_i profiles measured by the ISP. The detail description of the behavior of ions in the divertor plasma in LHD remains as a matter to be discussed after obtaining the results of precise profile measurements of T_i. In addition, further research on the interpretation of *I–V* characteristics of ISP for several plasma conditions would increase the reliability of evaluation of T_i. These kinds of investigation are progressing in the linear divertor simulators NAGDIS-II in Nagoya University [13] and PSI-2 in IPP-Berlin [14].

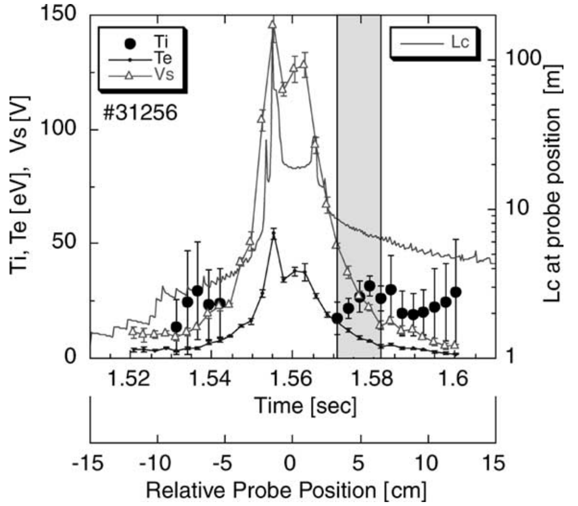

Fig. 5. Profiles of the T_i, T_e, V_s and L_c in the divertor leg along the path of the ISP probe. The time axis indicates the passing time of the ISP. The L_c structure is independent of the time evolution. The precious results of T_i estimation were obtained in the hatched region.

4. Conclusions

The T_i measurement using the ISP has been performed in the divertor leg region in LHD. The satisfied *I–V* characteristics of the ion collector were obtained at the outer part of the divertor leg. In this region, simultaneous measurements of T_i and T_e showed reliable results for the first time in the LHD. The measured T_i was higher than the T_e. The spatial distribution of the evaluated T_i is qualitatively consistent with the results of calculations of particle's orbits around the edge and divertor region in LHD. In order to obtain the full profile of T_i in the divertor plasma, some improvements of the electrode's structure and the electric circuit are needed. A further direction of this study will be to realize the relationships of T_i between the divertor region and the edge or the core plasmas.

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